MODELING POWER PLANT COOLING WATER REQUIREMENTS:

A REGIONAL ANALYSIS OF THE ENERGY-WATER NEXUS

CONSIDERING RENEWABLE SOURCES WITHIN

THE POWER GENERATION MIX

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Water is used in power generation for cooling processes in thermoelectric power plants and currently withdraws more water than any other sector in the U.S. Reducing water use from power generation will help to alleviate water stress in at risk areas, where droughts have the potential to strain water resources. The amount of water used for power varies depending on many climatic aspects as well as plant operation factors. This work presents a model that quantifies the water use for power generation for two regions representing different generation fuel portfolios, California and Utah.

The analysis of the California Independent System Operator introduces the methods of water energy modeling by creating an overall water use factor in volume of water per unit of energy produced based on the fuel generation mix of the area. The idea of water monitoring based on energy used by a building or region is explored based on live fuel mix data. This is for the purposes of increasing public awareness of the water associated with personal energy use and helping to promote greater energy efficiency.

The Utah case study explores the effects more renewable, and less water-intensive, forms of energy will have on the overall water use from power generation for the state. Using a similar model to that of the California case study, total water savings are quantified based on power reduction scenarios involving increased use of renewable energy. The plausibility of implementing more renewable energy into Utah's power grid is also discussed. Data resolution, as well as dispatch methods, economics, and solar variability, introduces some uncertainty into the analysis.

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CHAPTER 1

INTRODUCTION

1.1 The Relationship Between Water and Power

Water conservation has been an important topic with the progression of climate change causing more frequent and longer droughts in many areas of the world. When discussing water conservation, water usage for power generation is usually not considered, even though the power sector, along with agriculture, is one of the largest water users in the continental United States. In 2010, thermoelectric power withdrew more water than any other sector, accounting for more than 45% of all withdrawals that year [1]. Power plants use water in their condensers to remove waste heat and can consume hundreds of gallons per megawatt hour of energy produced depending on the fuel type and the cooling technology used [2]. Plants with closed circuit cooling with cooling towers are mainly responsible for this large consumption. Once-through systems consume less water but require massive quantities of water to be withdrawn in order to adequately cool steam in the condenser. Dry cooling, mostly popular in many modern natural gas fueled plants [3], uses air to cool the condenser rather than water and therefore consumes no water; however, air is not as effective as water as a cooling fluid, especially on hot days, and increases capital costs of the plant as well as reducing the potential net energy output due to the powering of the fans [4].

Water, used in traditional thermoelectric power generation, will continue to be implemented as a cooling strategy, though there are ways to cut back on water usage in producing power, such as using more renewable types of energy, including wind and solar, which require no water. These have the additional advantage of outputting zero emissions.

1.2 Factors That Affect Water Use in Power Systems

Water use in power plants per unit of power generated can vary based on many different factors. The properties of the water used for cooling, such as water temperature and water availability, can have a significant impact on the power system. The warmer the water, the more water is needed to achieve a complete cooling process in the condenser and there is an observed drop in power production and efficiency, especially in those plants using once-through systems [5], [6], [7]. If water is not readily available, the reduction in power production and overall efficiency is more severely impacted [8]. In extreme cases, this could cause the plant to shut down until a time when conditions are more favorable for power production [9]. For this reason, power plants in warmer, drier climates can have problems, especially during times of drought or record high temperatures during summer months, both likely to increase in some regions due to climate change-induced global temperature increases. The time of year that the power is produced also has a big impact. Cooler water temperatures in the winter can lead to increase in efficiency. These constant fluctuations make modeling water use in power systems very complex. Power and water use data that are available must be relied upon in order to accurately represent water use in power systems.

1.3 How Power Is Distributed

The North American Energy Reliability Corporation (NERC) is responsible for many of the grid operations in the United States and creates and enforces many of the standards for reliable grid performance [10]. Balancing authorities (BA), as the name suggests, are responsible for balancing the power grid in certain regions. These regions maintain power dispatch independently but can interchange power between one another [11]. This study focuses on the Western Interconnection, consisting of 37 balancing authorities seen in Figure 1.1. Specifically, the balancing authorities largely responsible for managing grid operations in Utah and California, PacifiCorp (PACE) and California Independent System Operator (CAISO), respectively, will be analyzed.

1.4 Solar Potential in Utah

When considering the solar potential in Utah, it seems to be an underutilized resource since, according to the Energy Information Administration, the amount of potential solar

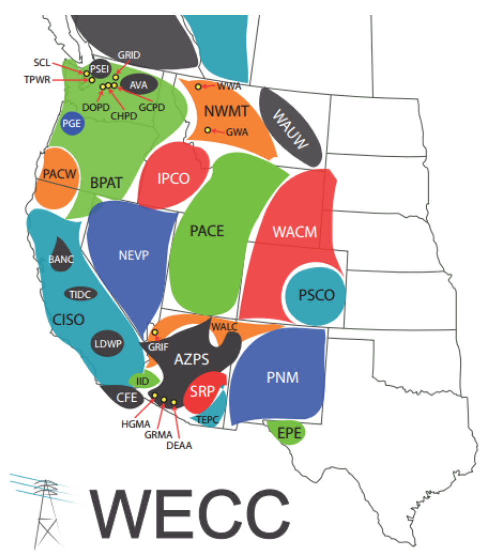

Figure 1.1. Map of Balancing Authorities in Western Interconnect [12].

energy to be absorbed ranges from 5.21 – 7.03 $kWh/m^2/day$ across the state [13]. Currently, solar power accounts for less than 0.1 percent of Utah's total energy generation [14]. Implementing solar energy into the power grid is becoming more plausible due to the renewable energy becoming more affordable each year. It would also have many benefits, including a significant reduction in emissions as well as water use.

1.5 Scope of Thesis

This work will focus on modeling the energy-water nexus and the implementation of solar technology into the power grid to replace conventional thermoelectric practices in order to quantify the water savings using Utah as a case study. This area is chosen due to its drier climate and susceptibility to drought. Water savings will be quantified by assuming some percentage replacement of conventional thermoelectric power generation of certain fuel types, namely coal and natural gas, with photovoltaic systems that require no water to operate. This will also take into account the land area required to produce this power with PV solar panels based on solar data for Utah.

1.6 Thesis Outline

Chapter 2 includes a literature review focused on how power plants behave based on water properties, water modeling from power plants from a given area, and how the energy-water nexus can be modeled. Chapter 3, titled 'Quantification and regional comparison of water use for power generation: A California ISO case study,' which was published in Energy Reports, explores the idea of using live data to monitor power plant water use so that a person could know how much water is being withdrawn or consumed based on the power being used by that person and specifically uses data that apply to those living in the CAISO subregion. Chapter 4, titled Impacts of 'Increased Penetration of Renewable Power Generation on Water Use in the State of Utah,' analyzes the effect of increasing solar power on both withdrawals and consumption in Utah as well as the feasibility of implementing solar power. Lastly, Chapter 5 will summarize the major findings of this work and conclude the thesis.

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CHAPTER 2

A LITERATURE REVIEW OF THE ENERGY-WATER NEXUS

2.1 Literature Survey

Water is used to produce energy, typically for cooling, and it take energy to purify and transport water. This is typically known as the energy-water nexus. This study focuses on the water used for the power side of the energy-water nexus. Quantifying water usage from power generation is typically done by applying a ‘water factor’ to the power generation data of a given plant. The water factor is expressed in terms of the volume of water per unit of energy produced, typically gallons per megawatt hour. Macknick, et al., in their paper “Operational water consumption and withdrawal factors for electricity generating technologies: A review existing literature,” tabulate different water factors for plants based on fuel type and cooling type for both water withdrawals and consumption compiled from values found from literature [1]. The study also includes water use factors observed for different types of renewable energy. Fuel types such as solar thermal and geothermal that run on a Rankine cycle have similar water factors to other conventional fuel types while other renewable fuel types such as solar PV or wind turbines use very little water since they do not need water for cooling and usually use it only for cleaning purposes. These water factors form the basis of water energy modeling, and power generation data, fuel type, and cooling system of a plant are all that is needed to get an estimate of the water that is being withdrawn and consumed. Because of the uncertainty involved when modeling water use for power generation, Macknick, et al. present a range of values: max values, min values, and median values obtained from literature.

This uncertainty can be explained by looking at factors affecting power production in plants. Quantifying water use at the power plant level is a well-explored topic. Plants of all fuel types as well as cooling systems have been modeled to determine what potential water properties can affect plant performance as well as how the different plant properties can affect water use in plants. Modeling water use from power on a regional scale has also been analyzed, although considerably less since there is much more uncertainty involved. Mostly researchers use a case study focused on a certain area, power region, or a national scale. Most of these analyses focus on future projections of water use as power requirements increase or decrease based on certain scenarios. However, few analyses have tried to quantified water savings as more renewable energy is implemented into the power grid.

The uncertainty in water factors is better understood by analyzing plants on an individual level. Many factors can affect water use in power plants including climate factors as well as the operating properties of the plant itself. Using a model developed in [2], it was found that a 1°C increase in cooling water can decrease a power plants electricity generation by 2%. In [3], the model further analyzes the percent decrease in power reduction based on the cooling type. It was found that once-through cooling systems were much more affected by changing air temperatures, with a power decreases of up to 4.55% annually. For plants with cooling towers, the power decrease was up to 0.21% annually. Similar results are found in [4], which shows how power generation can decrease under different climate change scenarios up to the year 2060 due to changing water resources. It was shown that the thermoelectric power potential could decrease by up to 20% in some areas in Europe. Much research has been done finding similar results: [5] found a 1°C water temperature rise can decrease power output by 2.2-2.5% in nuclear plants, [6] found that the demand for water increases with temperature change in cooling water and reduces the power output and efficiency, [7] used a system dynamic model to find that annual load reductions can be as high as 5.1% due to water temperature for some plants based on future projections, and [8] states that if the temperature of the cooling water gets too hot, the plant may need to shut down until there are more favorable conditions. These and many more research articles attempt to quantify how water properties such as temperature or availability affect power plant operations. Any of these changes due to increased temperatures in air or water can have an impact on the amount of water required to produce one unit of power. These studies all demonstrate the uncertainty that can be introduced when trying to model systems of plants on a larger scale like that of a state or NERC region.

There are different reasons for modeling the energy water nexus. In [9], models seek to optimize economic dispatch of power system and water production showing the total money savings found based on certain scenarios with varying amounts of water storage potential. Other research involves modeling the energy water nexus and changing certain variables such as water or energy prices, power demand, or water availability. A model for analyzing the energy-water nexus is developed using bond graphs for subsystems in [10], which can more accurately model how water and energy affect one another. This has the potential to see how more renewable integration can affect the energy water nexus as a whole, although no such analysis is done in the paper. [11] applies an energy-water nexus model to Texas to see how reducing waste water affects power production and how reducing overall power generation would affect water use. Another case study in Texas observes how changing water prices can affect water use in power plants and found that increased water fees can decrease water withdrawals for power by 75% and consumption by 23% in the ERCOT region [12]. Many studies in the water-energy nexus project future water use due to assuming scenarios that limit carbon production. In one such study, future power generation is modeled based on policy-driven scenarios and uses Macknick's water factors to relate power predictions to water use [13]. They found that more energy efficiency in commercial buildings and renewable energy will have the greatest effect in reducing water due to power production. A more detailed study of this aspect is found in [14] that further quantifies the water use based on these scenarios and is focused in many different subregions in the United States. Calculating water use for power is similar to calculating emissions from plants so studies of the two can be combined. One study shows hourly water consumption and emission rates for 252 power plants in Texas, illustrating that there can be tradeoffs between the two and quantifying the amount of emissions and water savings by replacing coal plants with natural gas plants [15].

The most similar study to this work was done by NREL and is found in [16]. They use a ReEDS model to predict the effect of high solar penetration on national withdrawals and consumption based on future predictions of power generation under certain scenarios. National reductions in withdrawals and consumption, as well as PV potential and implementation, are presented spatially based on the scenarios. The NREL study differs from this work in that they used national water factors to calculate water withdrawals and consumption while this work uses water factors calculated for Utah on a monthly basis based on energy and environmental data from EIA. This gives a more regional-specific value for water use reductions as well as reducing some of the uncertainty by not applying a median value for water factors found in [1]. National water factors are only used if no environmental data are available for a given power plant. They also do not consider the potential land use required for implementing PV but recommend that analysis in future work.

2.2 Literature Survey in Relation to Thesis and Thesis Introduction

The first part of this research (Chapter 3) differs from much of the research done in the energy-water nexus. Rather than exploring future water use from energy-based scenarios or see how changing certain properties affects power generation water use, this study will focus on present water use by modeling real-time water use from energy production in the CAISO region. This region is chosen due to its high quantities of power data availability, in this case, up to a 5-minute resolution. Many buildings have energy sensors that monitor the amount of energy being used by a building. This study will take that further by showing how much water has been withdrawn and consumed due to that energy produced. This is done using hourly real-time energy data based on the fuel mix and applying Macknick's water factors [1] based on that fuel mix. Application to a building could help to increase public awareness of the water being used due to personal energy consumption and further encourage energy conservation and, therefore, water conservation.

In Chapter 4, the second part of this research will be similar to many of these studies in that it will assess the total water use from power generation based on data but in the State of Utah. This presents a greater challenge since energy data for power plants under PacifiCorp are only reported monthly to EIA and therefore lack the resolution of other places like CAISO. This study will similarly examine how reducing power generation in

Utah will affect water use but will assume that this decrease is cause by increased energy from solar PV in the state. The percent reduction of water withdrawals and consumption are calculated by replacing some percentage of conventional thermoelectric power generation that uses coal and/or natural gas as a fuel. The total land area required for solar implementation will be calculated as well as an assessment of how much of that area could potentially be covered by rooftop PV solar power. In this way, increased solar PV production is related to the reduction of water use from power generation.

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CHAPTER 3

QUANTIFICATION AND REGIONAL COMPARISON OF WATER USE FOR POWER GENERATION: A CALIFORNIA ISO CASE STUDY

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Quantification and regional comparison of water use for power generation: A California ISO case study

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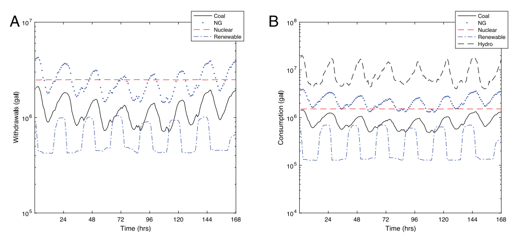
HIGHLIGHTS

- Water use for power generation quantified by generation mix using factors in gal/MWh.
- Generation under different balancing authorities is compared on an hourly basis.
- Overall water consumption and withdrawals calculated over one week in California ISO.
- Uncertainty is quantified according to water use factors obtained from literature.
- This method can assist with controlling electrical power use based on water use.

GRAPHICAL ABSTRACT



- Total water withdrawals(A) and consumption (B) for different power generation fuel types over one week during the summer (19-26 August 2015).

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ABSTRACT

Analysis of water use for power generation has, in the past, focused on large geographical regions and time scales. Attempting to refine this analysis on the time and spatial scales could help to further understand the complex relationships involved in the energy–water nexus, specifically, the water required to generate power. Water factors for different types of plants and cooling systems are used from literature in combination with power generation data for different balancing authorities to model water use as a function of time based on the fuel mix and power generated for that region. This model is designed to increase public awareness of the interrelation between the energy consumed and water use that can be taken into account when making decisions about electrical energy use. These results confirm that areas with higher renewable energy penetration use less water per unit of power generated than those with little or no renewable technologies in the area, but this effect is heavily dependent on the distribution of the types of renewable and conventional generation used.

1. Introduction

Water is essential for thermoelectric power generation, and electrical power is used to treat and distribute water, in what is called the energy–water (or electricity–water) nexus (Scott et al., 2011; Cook et al., 2015; Bazilian et al., 2011; Sovacool and Sovacool, 2009). Water is used for cooling, removing waste heat in a power generation cycle, and the electricity sector is second only to agriculture in water use within the United States ("USGS: Thermoelectric Power Water Use in the United States" 2014). Water shortages and occurrences of drought have been increasing in recent years, especially in the arid western US, with California facing some of the most extreme water scarcity (California Natural Resources Agency, 2016). The amount of water used for each unit of electrical power

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will vary based on the grid's generation mix as well as method of cooling at a given climate and hour of the day. Water is considered to be withdrawn when it is diverted from a source and immediately returned to that source after use, water is consumed when it is not returned after use. Plants with once-through systems generally withdraw large quantities of water but have low water consumption while plants with closed circuit-cooling with cooling towers withdraw less but consume a lot more. One way of preserving water for power systems would be to not use water but rather air in what is termed dry cooling. However, this method is more expensive to implement and is not as efficient (Peer et al.). Another proposed way would be to increase the cost of water in order to encourage more frequent use of less water intensive power systems (Sanders et al.). In the case of California, the need for water conservation is a growing concern as drought continues to strain water resources in the area, and therefore, the water use in the power sector needs to be considered on a regional scale in order to know how to best allocate resources.

Quantifying water use on a regional scale can be useful when considering resource allocation or electrical generator dispatch, and can be used to increase public awareness of how much water is used in connection with power consumption in people's day to day lives. Leading thinkers at the energy–water nexus have identified a shift in perception that clarifies the relationship between these two interconnected resources as a critical need for conservation and environmental protection (Webber, 2016). Providing information about water use tied to electricity use could help to encourage conservation motivate water-concerned individuals to cut down on electrical power usage.

Water usage for power varies with the power generation mix, depending on: the fuel used by power plant, its efficiency, cooling technology, and ambient conditions. A group of researchers at the US Department of Energy's National Renewable Energy Laboratory have compiled a range of water withdrawal and consumption factors for different fuel technologies and cooling types based on power plants across the country (Macknick et al., 2011). Power generation systems typically include coal, natural gas, nuclear, and renewable technologies while the cooling systems range from once-through systems and cooling towers to dry cooling. These values relate water use to power generation in gallons of water consumed or withdrawn per megawatt-hour. Many of these water factors found by Macknick et al. can vary widely across a range of potential values for water use (Macknick et al., 2011). They are used here to give the maximum and minimum values as well as the median for each power system and cooling type considered.

This range of water factors introduces a great deal of uncertainty when assessing overall water use for a region of the power grid. Water use can vary based on the temperature of that water, with more water flow needed to remove the necessary amount of heat when the water's temperature is high (Koch et al., 2014; Kyle et al., 2013). Temperature differences can also disrupt plant operations, which results in less power being generated at any one time (Koch et al., 2014; Kim and Jeong, 2013; Linnerud et al., 2011). For example, a water intake temperature increase of only 3 °C can reduce the power output by 500 GWh/year for plants with once through systems, and 50 GWh/year for plants with closed circuit cooling (Koch et al., 2014). Even temperature shifts in the diurnal cycle could alter the water factors of certain plants.

The US Geological Survey (USGS) currently reports water use for power generation on the state level and only once every few years ("USGS: Thermoelectric Power Water Use in the United States" 2014). Increasing the temporal and spatial resolution associated with these calculations can also increase understanding of the relationships between water and power. This analysis will focus on the geographical area of at the level of balancing authorities, who coordinate between power generation facilities and power supply to the electrical grid. Furthermore, calculations here are made on an hourly time scale. While the balancing areas are large, it is difficult to attribute a specific generation mix at smaller scales, and reliable power generation data is reported on at least hourly scales for many of these areas. Fig. 1 ("FERC: Industries—RTO/ISO" 2016) shows a map of balancing authorities in the US These authorities are responsible for power generation and distribution in their given area, although they can trade and distribute power outside that region ("Glossary—US Energy Information Administration (EIA)" 2016). For example, power generated by the MISO region may end up being transferred and used in the PJM region. This paper focuses on the CAISO (California Independent System Operator) region as a case study due to the region's frequent reporting of generation data and the state's significant concerns about water availability. CAISO covers most of the geographical area of the state of California, as shown in orange in Fig. 1. A similar analysis with other balancing authorities can be conducted using the same methodology, allowing for comparisons between the generation mix in each region.

Here, overall water use for power generation will be modeled on a regional scale for a specific balancing authority area, more specifically in the CAISO region. Water use factors found by Macknick et al. (2011) are combined with generation data from the balancing authority to find an estimate of the total water used per megawatt hour for that region, in a specific hour. The full range of water factors (minimum to maximum) will be evaluated in this paper in order to show the potential spectrum of overall water use. By using these regional coefficients, this methodology can be used to describe how much water a specific facility or process is using indirectly based on its electrical power consumption.

2. Methods

Water usage in a power plant can depend on many factors including the cooling system that is used, weather, as well as the region the plant occupies. For this model, it is assumed that all power systems used closed circuit cooling with cooling towers. This assumption is warranted since the state of California water resource control board put in place a new regulation in 2010 that limits the amount of water withdrawn for once-through cooling systems, which withdraw much more water than other cooling systems and can be especially harmful to marine wildlife, and encouraging the modification of existing once-through systems to closed circuit cooling (California State Water Resources Control Board, 2016). This will also provide a minimum basis for the amount of water being used to generate power. Since this is not the case for many other regions, the authors will incorporate once-through systems into the model before the source code is released to the public.

Macknick et al. have compiled withdrawal and consumption numbers that represent the water used by the plant per unit of energy generated (gal/MWh) for each generation system and cooling type that will be used in coming up with a total water usage in a given area. Table 1 verifies that these water factors can be applied to the study area by taking three plants for each cooling system, once-through and cooling towers, and comparing the withdrawal and consumptions factors compiled by Macknick, et al. to those calculated using power generation data and water use data reported by EIA in 2015 (EIA). Water factors were calculated based on water usage data available from EIA.

It can be seen from Table 1 that, with the exception of the nuclear plant, all plants fit within the expected range of water factors reported by Macknick et al. Concerning the nuclear plant, its withdrawal number for the year is exceptionally large for that year considering that the withdrawal factor the previous year was

Fig. 1. Service regions for independent system operators with CAISO shown in orange (California Independent System Operator Corporation, 2016a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Comparison of withdrawal factors (WF) and consumptions factors (CF) with the withdrawal and consumptions factors reported by Macknick et al. (MWF and CWF respectively) for three plants of each cooling type. Water factors units are gal/MWh and capacity is in MW.

Plant name	Capacity	Fuel type	WF	CF	MWF	MCF
Cooling tower technology						
Mountainview generating station	1037	NG	197	154	150–283	130–300
Valley (CA)	691	NG	241	205	150–283	130–300
Etiwanda generating station	24	NG	1 137	962	950–1460	662–1170
Once-through systems						
Diablo canyon	2323	NUC	166 724	–	25 000–60 000	100–400
Dynegy moss landing power plant	2802	NG	19 418	–	10 000–60 000	20–100
Haynes	2425	NG	54 122	–	10 000–60 000	20–100

37,160 gal/MWh which does fit within NREL's range. Drought in California was more severe 2015 with low reservoir levels which may be the reason for the exceptionally high factor that year (NCEI). As discussed above, limited water availability can have a large impact on plant cooling systems.

In order to analyze the amount of water being used for power, it is necessary to first know how much power is being generated in a specific region and by what type power system. This is accomplished using an online API called WattTime (WattTime, 2016). WattTime provides open data on many balancing authorities in the United States including fuel mix data and carbon emissions data on an hourly and/or a five-minute basis. The fuel mix data is broken down into components of thermal, solar, wind, hydro, solar thermal, etc. depending on what is being used for generation in that area. The data for the CAISO region is broken up into thermal, nuclear, natural gas, and various types of renewable forms of energy generation such as solar, hydro, and geothermal. The term "thermal" here refers to those plants that produce their energy thermoelectrically. Since it is unclear how much of the thermal generation is divided into coal, natural gas, and nuclear power, it becomes necessary to break down the thermal generation using the EPA's power profiler ("How Clean Is the Electricity I Use?—Power Profiler | Clean Energy | US EPA" 2016). Based on data compiled by the EPA, out of the total power produced by thermoelectric generation, roughly 10% was produced by coal and 90% by natural gas in the WECC California sub region. However, the consideration of power generation units' contributions by percentage of total electrical generation (on a yearly basis) will introduce significant uncertainty, particularly at smaller, sub-yearly time scales, because the percentage of power generation at any given time is determined by the CAISO market (CAISO 2016b).

The next step is to verify the quality of the given data. This is done using a statistical analysis. Each point of the data is plotted as a function of the data point before to show how the data varies within the dataset. This was done using the BPA region due to the large quantity of data points provided, updating their power generation every five minutes. This data, taken from two different weeks in the summer and winter, is converted to hourly data and is plotted in Fig. 2 for each fuel mix. In this case, $Y(i)$ represents power data at time step i. A linear trend is observed in each of the data sets with no more than one outlier in a few of the plots. This shows that the data is of good quality and can be used in the analysis. There were some points in the data that were either nonexistent or contained no value; these were dealt with by a simple linear interpolation. For the CAISO region, this was a negligible concern, happening less than 0.1% of the time.

The model was built using MATLAB, an engineering computing software, which takes in data from WattTime and gives the overall

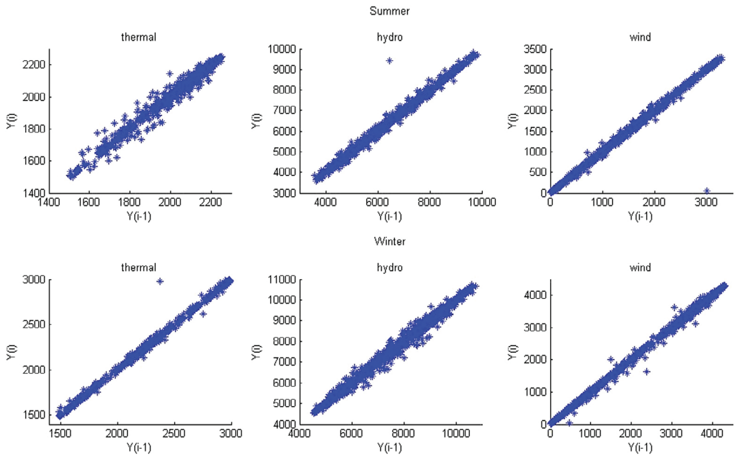

Fig. 2. Statistical analysis of data provided by WattTime for each power system dataset for one week of summer and winter.

water usage per megawatt hour based on the fuel mix at the given time. The process is illustrated in the below analysis.

Let x be the area or balancing authority where the data is taken, and i be the generation fuel type of the area x at time n. The total generation of each power plant type is divided by the total generation in that hour to produce a weighting factor (WF) as shown in the equation below.

$$WF_i^n(x) = \frac{P_i^n(x)}{\sum_{i=1}^{N} P_i^n(x)} \tag{1}$$

where P is the power produced by generation fuel type i at time n, where N is the total amount of different generation types. A weighting factor is generated for each power generation facility at each hourly time step. These factors are then multiplied by Macknick's withdrawal and consumption factors, defined as MW and MC respectively, for each generator, i, and added together at each time step, n, to come up with a total water use factor at each hour for both withdrawals and consumption as shown below.

$$W^n(x) = \sum_{i=1}^{N} WF_i^n(x) * MW_i \tag{2}$$

$$C^n(x) = \sum_{i=1}^{N} WF_i^n(x) * MC_i \tag{3}$$

where W and C are the withdrawal and consumption factors in gal/MWh at time n. These water numbers can then be multiplied by total hourly energy use in a building or city to estimate the amount of water being withdrawn and consumed at each hour of the day. This can be done for each specified balancing authority x such as BPA, CAISO, ISONE, MISO, or ERCOT depending on the data available.

3. Results and discussion

Hourly data was taken for the CAISO region during the summer and winter seasons for one week in August of 2015 and February of 2016. The results are shown in Figs. 3–5. Fig. 3 shows the average weighted water factors, in gallons per megawatt hour, throughout the week. It also shows the large range at which these water factors can fluctuate which is due to the large range of water factors observed for each individual plant fuel type. This means that there is some related uncertainty introduced when determining how much water is being used as a function of power consumption.

Fig. 2 shows the overall water withdrawals and consumption in the summer and winter months based on the power production values from WattTime and the water factors from Macknick et al. (2011). The water use can be seen to fluctuate more in the summer possibly due to the greater accessibility of renewable forms of energy during that time. This plot uses overall energy data to calculate water use over time, but the water factors can also be applied to building energy data to see how much that water is associated with the power being used in that building. This can be useful in order to increase awareness of where water is being used and can also be valuable in times of water shortages when considering what resources can be reduced in order to save water. Reducing water consumption from power use often leads to reduced emissions from plants as well. Typically, the more power is generated at a given time, the more greenhouse gases and other pollutants are released into the atmosphere; however, the relationship between power generation, water use, emissions, and other environmental impacts is complex and often involves trade-offs between desired environmental outcomes (Peer et al., 2016). This model should be used in conjunction with a similar model incorporating emissions resulting from power generation to evaluate whether decisions affecting power generation units would benefit both water conservation and emissions reductions.

Withdrawals and consumption are broken down by generation type in Fig. 5. This illustrates the power plant fuel types that are using the most water. It can be seen that in both summer and winter, the most amount of water being consumed is from hydroelectric plants. This is to be expected because while water passing through a hydro plant is not considered to be withdrawn, hydro plants can consume large amounts of water from the added evaporation due to creating a large reservoir (Mekonnen and Hoekstra, 2012). The green line in Fig. 5 represents the water used by all renewable forms of energy. Renewable energy, despite its growing popularity and accounts for almost 30% of power generated in the CAISO region (see Fig. 6), uses the least amount of water with most of the water used is the result of geothermal

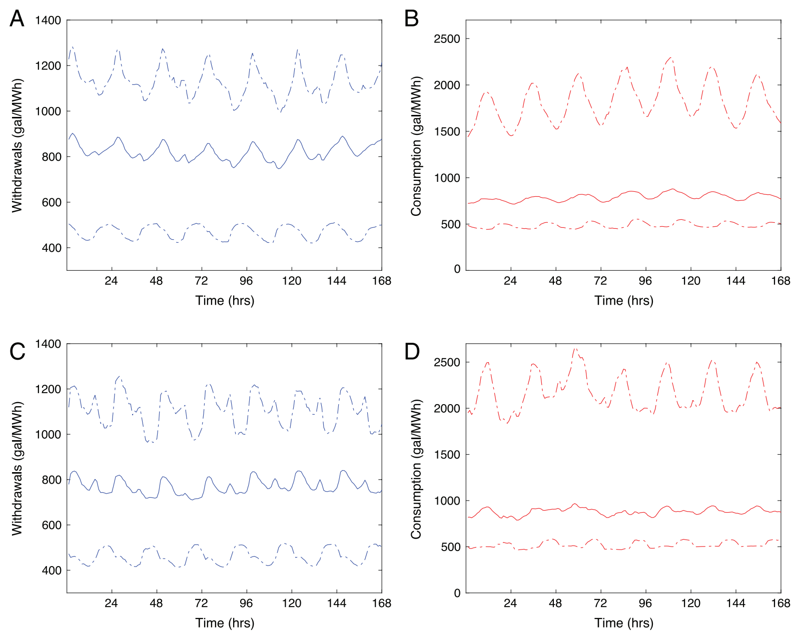

Fig. 3. (A) Summer withdrawal factors. (B) Summer consumption factors. (C) Winter withdrawal factors. (D) Winter withdrawal factors.

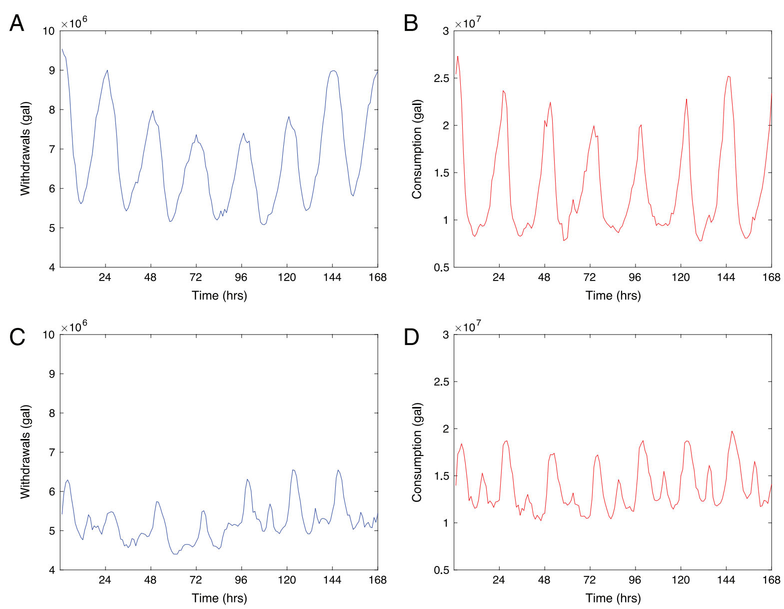

Fig. 4. (A) Summer total withdrawals. (B) Summer total consumption. (C) Winter total withdrawals. (D) Winter total consumption.

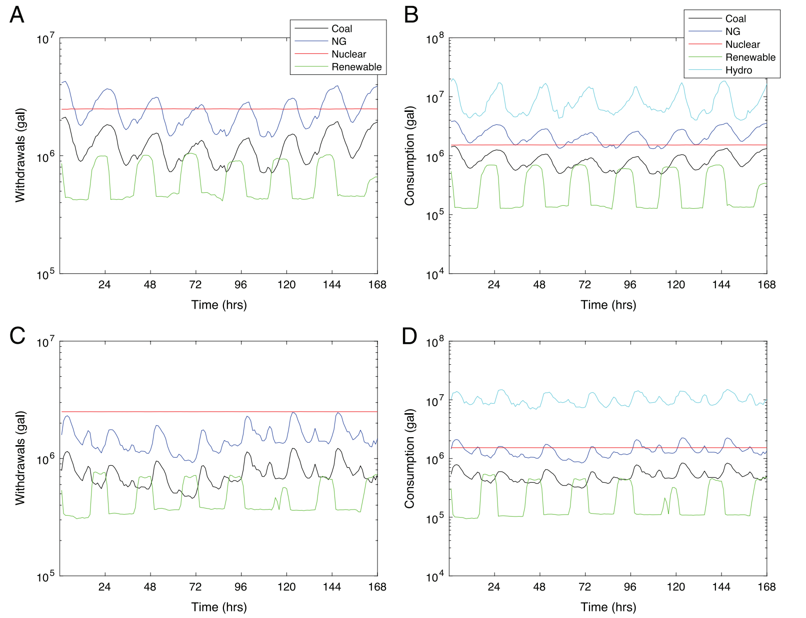

Fig. 5. (A) Summer withdrawals by generation type. (B) Summer consumption by generation type. (C) Winter withdrawals by generation type. (D) Winter withdrawals by generation type. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

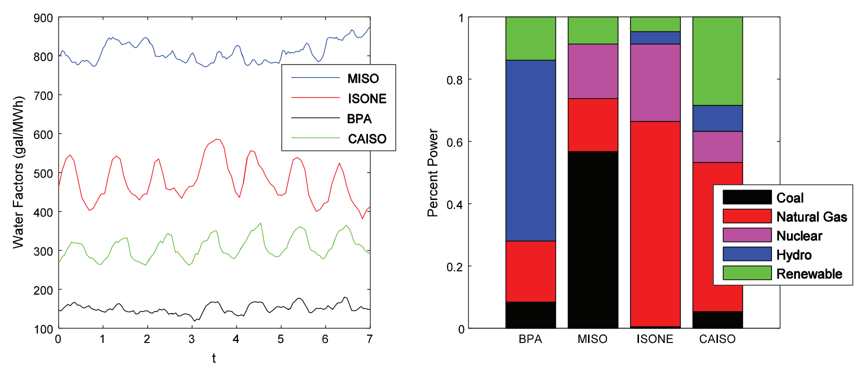

Fig. 6. Water factors for each balancing authority in the month of August 2015 (left). The average amount of each fuel type used by each balancing authority in August (right).

and solar thermal power generation. These systems can still use as much water as conventional thermoelectric generating systems though it is greatly reduced in the case of geothermal (Macknick et al., 2011). In contrast, solar PV and wind energy use almost no water (IRENA, 2015).

4. Conclusion

This analysis results in a new method for perceiving water use as related to energy consumption. The water consumption and water withdrawals made for power generation were quantified according to the generation mix using factors in gal/MWh. Water withdrawals and consumption were simulated down to an hourly time scale in order to illustrate changes in water use throughout the day, focusing on two weeks during summer and winter for the California ISO. Uncertainty in these calculations is based on the range of expected values found in the literature, and is illustrated along with the withdrawal and consumption values to illustrate the magnitude of uncertainty associated with this method. Water usage from power in regions with greater renewable power generation penetration has also been compared to water use in regions with less renewable energy in the generation mix.

Although there is significant uncertainty when relating water use to power generation, this uncertainty may be quantified and was presented here along with the water withdrawal and consumption estimates. This can be used to better understand how water use will change as a result of changes in the generation mix; and is critical to understanding how power production affects the water supply on a regional scale. More detailed information on the power plants in a specific region will help to reduce this uncertainty; when the specific cooling technology used, ambient conditions, and thermodynamic operating conditions of the plants are considered, the range of potential values for water consumption and withdrawals attributed to those plants are smaller. Future work by the authors will address reducing uncertainty with the water use predictions, and investigating the impacts of renewable power generation integration on water use in a given region.

When an individual or facility manager could see how much water is being used due to their own power consumption, this information can be used for education and conservation. Using less power, rather than only limiting municipal water usage, helps to protect water resources as well. This work provides a simplified method for quantifying the amount of water savings with a given amount of electricity savings. Water usage from power should also be considered more thoroughly during the handling of water shortages, just as with agricultural or other public uses. Quantifying of this water use could further aid in the decision making process when water allocations are made.

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CHAPTER 4

IMPACTS OF INCREASED PENETRATION OF RENEWABLE POWER GENERATION ON WATER USE IN THE STATE OF UTAH

4.1 Abstract

Thermoelectric power plants withdraw more water than any other sector in the United States. Reducing water use in the power sector can help to alleviate water stress in vulnerable areas and can be achieved using renewable forms of energy that are less water intense. The quantity of water saved due to reduced thermoelectric power generation depends on the fuel mix and cooling technology used in a given area. In this work, publicly available data for power generation and water use are integrated to quantify the amount of water that can be saved by switching from fuels such as coal and natural gas to less water-intensive technologies. Here, increasing amounts of solar PV power generation are considered in the state of Utah, taking into account the plausibility of the implementation of more renewable energy into the power grid. It was found that by reducing 30% of total yearly power generation from coal and 15% from natural gas, water consumption would be reduced by 35% and 7%, respectively. It was also estimated that implementing rooftop solar to its fullest potential in the state could potentially account for 16% of the yearly power generation. Dispatch methods, economics, and solar variability cause variation in

the overall quantities of water saved and the low resolution of the power data provided for Utah introduces additional uncertainty.

4.2 Introduction

Water allocation is an important issue in the western United States since many states are susceptible to or are currently in a state of drought. Typically, when considering water conservation, other sectors such as agriculture or public supply are considered first while the power sector is generally overlooked, although it is one of the largest water users in the United States, withdrawing more water than any other sector in 2010 [1]. Power generation uses water for cooling, and water purification and distribution also uses power, forming what is now called the energy-water nexus. The use of modeling to better understand the energy-water nexus has been attempted in many different regions. Stillwell, et al. analyze the energy-water nexus in Texas and quantify the effects on water if power is reduced and vice versa [2]. Sanders, et al. show how changes in water pricing can affect plant withdrawals and consumption for plants in Texas [3]. Studies have also been done to model the energy-water nexus in the Gulf Cooperation Council [4], [5]. Future national water withdrawals and consumption savings are calculated in a study conducted by NREL [6] based on predictions of power use under different solar power scenarios although the land use requirements are not considered. This study, like the NREL study, provides increased understanding of how the implementation of more renewable and water-conserving sources of power generation, such as solar PV, can affect the withdrawals and consumption of thermoelectric power plants. Here the focus is specifically on the state of Utah, where its desert climate can make it susceptible to water shortages, under different power reduction scenarios and based on presently available data. Land use requirements for different amounts of solar PV power generation are also considered.

Solar PV power production is becoming less expensive, making the implementation more plausible in many areas of the world. This is especially true for Utah, like much of the western United States, which is considered to have a dry climate [7]. According to the U.S. Energy Information Administration (EIA), Utah has a solar potential in the range of 5.21 – 7.03 kWh/m2/day [8], as well as open land space where additional solar generation can be situated in addition to the rooftop solar generation portfolio. Utah's solar market has experienced rapid growth in over the past decade, from only 100 kilowatts of power production in 2006 to 140 megawatts in 2016 [9]. Local nonprofit Utah Clean Energy is continuing to encourage the growth of the solar market and recently produced a ten-year plan that seeks to improve solar production in Utah by making it more accessible, affordable, as well as overcoming many of the challenges in permitting, interconnection, and energy storage [9]. Renewable energy may reduce water use in addition to reducing emissions related to power generation. As photovoltaic systems increase in their share of the power generation portfolio, water conservation benefits could be observed from the water resources that would normally be used for thermoelectric cooling. Most of Utah's plants are powered by coal and commonly use cooling tower technology [10]. These are more effective than their once-through counterparts in this area due to the dry climate and limited water resources, but cooling tower technology consumes large amounts of water. If this water can be saved through reduce power usage, it can be implemented in other sectors.

Analyzing the energy-water nexus in Utah presents a unique challenge since, unlike

California which provides hourly generation data, Utah only has limited data available, reporting generation data monthly through the Energy Information System (EIA). Utah is part of the Western Interconnect region, shown in Figure 4.1 [11], of the North America Energy Reliability corporation (NERC) who are responsible for most grid operations in the United States [12]. Utah provides power from 120 generating facilities. Although it is not possible to determine the provenance of electricity purchased from the grid at a given time, Utah is a net exporter of electricity [13], therefore the focus is on the power generation stations located within the state. In 2015, the average percentage of power coming from coal was 75%, natural gas 20%, with less than 5% being generated by renewable energy consisting of mostly hydro power (1.8%), geothermal (1%), and wind power (1%) while very little was generated by solar (< 0.1%) [10]. The distribution of fuel sources providing for Utah's electricity generation in 2015 is provided in Figure 4.2(a), while the distribution of renewable sources in the same year is broken down further by primary energy source in Figure 4.2(b). The monthly power distribution is shown in Figure 4.2 based on EIA data [10].

There have been many different studies on how renewable energy can reliably be implemented into the electrical grid. Studies include power quality and discussing different methods and devices that can improve overall power quality in renewable energy [14] as well as how distributed generation can incorporate renewable energy [15], [16], [17] and how a 'smart grid' can overcome many of the problems with renewable energy and help to meet environmental goals [18], [19], [20], [21]. Implementing storage is also a necessity when integrating renewable energy; different types of storage and how they can be incorporated with renewable energy has also been analyzed [22], [23], [24]. Since the

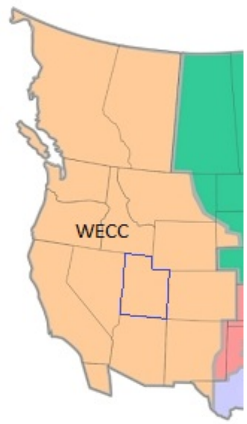

Fig 4.1. Map of Western Interconnection (WECC) and Utah (highlighted in blue).

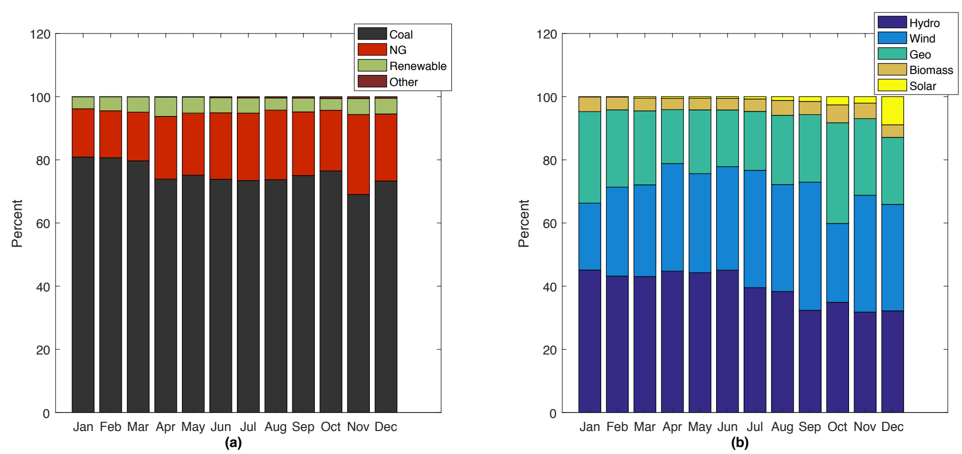

Fig. 4.2. Percent power distribution for (a) fuel types for Utah in 2015 and (b) renewable power by energy source for Utah in 2015.

integration of renewables into the grid system is a complex and heavily researched topic, this paper will only focus on the potential for renewable integration to conserve the water supply in Utah, while comparing these numbers to the land area required for a given amount of PV generation without focusing on implementing storage techniques or unique spatiotemporal challenges posed by distributed generation on the existing electrical grid.

This work quantifies the amount of water than can potentially be saved by implementing solar PV technology, using no water in day-to-day operation, compared with the grid's current a percentage of coal and natural gas fueled plants. Total water use is calculated monthly based on four different scenarios: 15% of total power is reduced from coal plants, 15% of total power reduced from natural gas plants, 15% of total power reduced from both natural gas and coal plants, and 30% of total power reduced from coal plants. The total water use is estimated from publicly available data about the existing fuel mix and used as a base case. In addition, the percent of total water saved is calculated for different combinations of reduced coal and natural gas plants incrementing the power for coal and natural gas plants by 5% for up to 30% for coal and 15% for natural gas (overall 45% decrease). This will be accompanied by the total land area needed for the PV array in order to generate enough power to make up a significant fraction of energy produced by power generation in the state.

4.3 Nomenclature

A_{PV}	Area of PV cells required to produce energy E_{sol}
A_{panels}	Area of the PV panels in South Jordan study
$A_{rooftop,Utah}$	Total estimated rooftop area in major counties

α	Solar angle
b	Boolean value to determine if a plant is on or offline
β	Panel tilt angle
C	Total consumption
$C_{reduced}$	Reduced consumption assuming supplemented solar
CF	Consumption factor in gal/MWh for a given year
CSJ	Number of customers in South Jordan study
Cons	Rate of water consumption for power in a given year
E	Total generated energy
$E_{building}$	Energy generated by a building
E_{sol}	Desired energy generated by solar energy
{F}	Set of all fuel types of all plants in Utah
f	Fuel type of a power plant
G	Variable indicating what percentage of total energy generation is from solar
H	hours of operation of cooling system in a given year
HS	Average household size in South Jordan, Utah
I_{GT}	Incident solar radiation rate
i	Index of a specific plant
j	Indexing a specific plant in {x}
K	Total number of cooling systems in plant i
k	Index representing a cooling system in plant i
L	Total number of timesteps
l	Timestep

m	Timestep representing a month of the year
N	Total number of plants in Utah
N_{panels}	Number of solar panels in South Jordan study
η_{Inv}	Efficiency of inverter
η_{PV}	Efficiency of PV panel
P	Population of Salt Lake, Utah, Davis, Weber, and Washington counties
W	Total withdrawals
$W_{reduced}$	Reduced Withdrawals assuming supplemented solar
WF	Withdrawal factor in gal/MWh for given year
With	Rate of water withdrawals in a given year
{x}	Set of fuel types of a specific fuel type
x	A specific fuel type

4.4 Methods

The Energy Information Administration has monthly energy data for 120 plants in Utah as well as environmental data including water usage for most plant cooling systems [10]. Data from 2015 were used as they were the most recently available from the sources used when the analysis was performed. The data collected on the energy side for this analysis are the monthly generation data, the plant fuel type, the total generation for that year, and the plant ID. The plant ID is collected to connect the plants power data to its environmental data. On the environmental side, the data collected was plant ID, the type of cooling systems used by the plants, the withdrawal rate (gal/min), the consumption rate (gal/min), and the hours in service for that year. These data were used to obtain a yearly overall water factor (gal/MWh) for that year. Many of the plants had multiple sets of data for multiple cooling systems which had to be combined together to get an overall water factor for that plant. This was done using the following two equations for withdrawals and consumption of plant *i*.

$$WF_i = \frac{1}{E_i} \sum_{k=1}^{K} With_k * H_k \tag{4.1}$$

$$CF_i = \frac{1}{E_i} \sum_{k=1}^{K} Cons_k * H_k \tag{4.2}$$

where *With* is the withdrawal rate, *Cons* is the consumption rate, and *H* is the number of hours of operation of cooling system *k*. *K* is the total amount of cooling systems for plant *i*, and E is the total energy generated for plant *i*. Water data for cooling were available for the top eight thermoelectric power plants, accounting for almost 85% of the total power generated. For plants that had no cooling data, values for the water factors were assigned manually using values from Macknick et al., which has average water factors based on plant fuel and cooling types [25]. Total withdrawals and consumption, *W* and *C*, respectively, are then calculated for a given month m.

$$W^m = \sum_{i=1}^{N} WF_i * E_i^m \tag{4.3}$$

$$C^m = \sum_{i=1}^{N} CF_i * E_i^m \tag{4.4}$$

where *E* is the total energy generated during month *m* of plant *i*, and *N* is the total number of plants. This gives a baseline amount of total withdrawals and consumption for the year being analyzed.

The method of reducing a certain amount of power from a specific fuel type is similar to the method above. There must be some value *b* that determines whether or not the plant is online, this is multiplied by the energy produced by plant *i* and is represented by a 1 or a 0 depending on whether or not it is online. Whether *b* is 0 or 1 depends on the fuel type of plant *i*. For this analysis, plants of certain fuel type are taken offline in descending order by yearly generation. The value *b* will determine if the plant is online, offline, or operating on a reduced capacity. With this defined, the total withdrawals and consumption can again be calculated without any water being used for the offline plants.

$$W_{reduced}^{m} = \sum_{i=1}^{N} WF_i * (E_i^m * b_i(f_i)) \tag{4.5}$$

$$C_{reduced}^{m} = \sum_{i=1}^{N} CF_i * (E_i^m * b_i(f_i)) \tag{4.6}$$

In determining the value for *b*, let f_i be the fuel type of power plant *i*, and let {F} the set of all fuel types. A set of all identical fuel types, such as coal, is defined as {x} such that {x} ⊂ {F}. Assuming that solar power is supplanting some percentage of power produced by plants with fuel type x, in this analysis coal and natural gas, a reduced value of total withdrawals and consumption at month m can be obtained separately for both coal and natural gas plants. Power plants with fuel types not a member of fuel type x will not have their power reduced while, depending on the amount the solar energy produced, the plants with fuel type x may have their power reduced. This is illustrated below.

$$b_i(f_i) = \begin{cases} 0, & f_i \in \{\mathrm{x}\} \;\&\; G_x \geq 0 \\ -\dfrac{G_x}{E_i^m}, & f_i \in \{\mathrm{x}\} \;\&\; G_x < 0 \;\&\; |G_x| < E_i^m \\ 1, & f_i \notin \{\mathrm{x}\} \; or \; (G_x < 0 \;\&\; |G_x| > E_i^m) \end{cases} \tag{4.7}$$

where

$$G_x = E_{sol} - \sum_{j=x_0}^{x} E_j \tag{4.8}$$

where E_{sol} is the energy generated by solar energy and x0 is the first plant of fuel type x to appear in {F}. The subscript *j* is the plant number of fuel type x such that the energy is summed from the first plant up until plant x. This variable *G* will be positive if the energy generated from solar is greater than that of the total power produced by plants x_0 through the current x, and negative otherwise. When *G* transitions from positive to negative, this means that all the desired amount of power is now assumed to be generated by solar instead of by plants with fuel type x. If more power is diverted than is needed, the excess power is returned to plant *i* as seen in the second condition of *b*.

The amount of power assumed to be generated by solar PV forms some percentage of the state's total energy generated in 2015. For grid integration without associated energy storage technology available, a simple approach is used to associate a given amount of energy with a given area needed for rooftop PV. This approach involves optimizing the rooftop area needed to perfectly match the electrical needs of a load. More details about this approach can be found in [26]. By minimizing equation 4.9 below, varying the area over the timestep *l*, the minimum area for the required load can be found.

$$\Delta = \left(\sum_{l=1}^{L} E_{load_l} - A_{PV} * \eta_{Inv} * \eta_{PV} * I_{GT_l} * \sin(\alpha + \beta) \right)^2 \tag{4.9}$$

where A_{PV} is the minimum area required for PV to meet the required load, E_{load} in this case is the required energy to be produced, I_{GT} is the solar insolation at timestep *l* and has been found using TMY3 data for Salt Lake City, η_{inv} and η_{PV} are the efficiencies of the inverter and the PV cell, respectively, and α and β are the solar angle and the cell tilt angle, respectively. For this analysis, the efficiencies are set to be 0.95 for the inverter, and 0.15 for the solar cell. The cell tilt angle is set to be 40º, equal to the latitude angle of Salt Lake City. Using the tilt angle as the latitude angle has been shown to be the optimum angle to maximize the power output of a solar collector [27], [28], [29], [30]. The solar insolation data have been summed over each month to match the monthly power data provided by EIA.

Once a total area has been determined, it is compared to estimates of Utah rooftop solar potential of the major counties in the state. A study done by Rocky Mountain Power estimated the number of solar panels that could be placed in a region in South Jordan, UT and the power that can be produced by these panels [31]. Extrapolating from these data as well as comparing population data from the major counties and the study area, a rough estimate of the rooftop area of the counties can be determined. By dividing the population of Utah's major counties from that of the study population, it can be roughly estimated how much potential area there is for solar panels within the state.

$$A_{rooftop,Utah} = N_{panels} * A_{panels} * \frac{P}{CSJ * HS} \tag{4.10}$$

where *N* is the number of panels found by be study, *A* is the area of the panels, *CSJ* is the number of customers in the study, *HS* is the average household size in the study area, and P is the total population of the major counties in Utah namely: Salt Lake, Utah, Davis, Weber, and Washington. Population and household size were found using the U.S. census bureau [32]. This method is inexact but can help to frame a scale of the solar PV potential in Utah and how it compares with the power currently generated and the land and rooftop area present.

4.5 Results

Total monthly water withdrawals and consumption based on the different power reduction scenarios by fuel type in comparison with the total monthly withdrawals and consumption without any Solar PV penetration are shown in Figure 4.3. Many of the natural gas plants are new and therefore much more water efficient or even dry cooled so therefore, coal plants have a much larger impact on the total water use overall. As would be expected, local minimum values for water use are observed in the months of April and November. This is likely due to more temperate temperatures reducing the need for buildings to heat or cool so that energy consumption will be reduced and therefore the power generated. Conversely, local maximums are observed in January and August likely for the opposite reason of extra energy needed to heat and cool homes. Figure 4.4 shows the monthly percent reduction in both withdrawals and consumption based on each scenario. It can be seen in scenarios reducing the natural gas fueled energy production that the withdrawals are more affected than the consumption while coal reduction has similar impacts on withdrawals and consumption. Having coal plants reduce their supply is the best way to maximize water savings. Reducing coal power production is possible if the base load decreases which may be possible through more distributed PV systems with the proper storage for when solar insulation is reduced or unavailable. The annual percent reduction in withdrawals and consumption based on some reduction in coal and natural gas fueled plants is shown in Figure 4.5. Both fuel types are increased in increments over the 2015 baseline in 5% intervals with a maximum of 30% reduction in coal plants and 15% in natural gas fueled plants with an overall total reduction of 45%. The 15% maximum in natural gas is due to the natural gas production never reaching over 20% of total generation

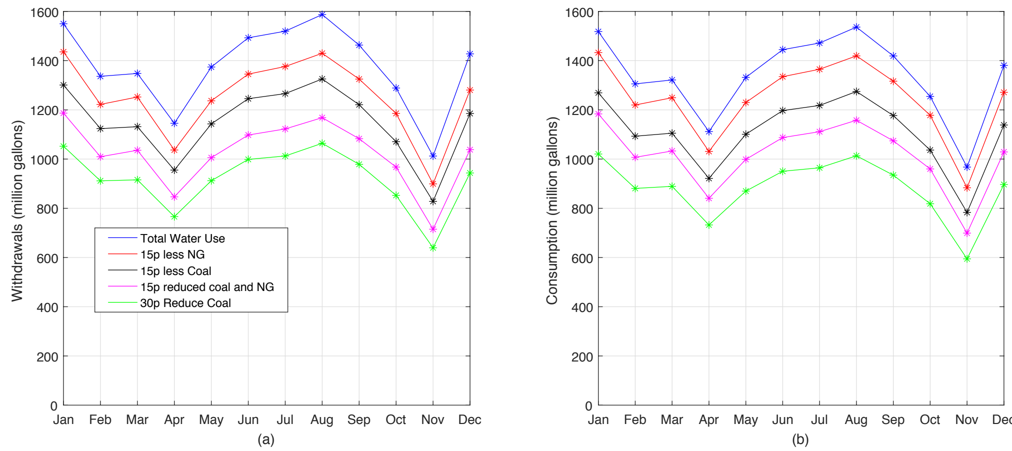

Fig. 4.3. Monthly total withdrawals (a) and consumption (b) based on different scenarios with data from 2015.

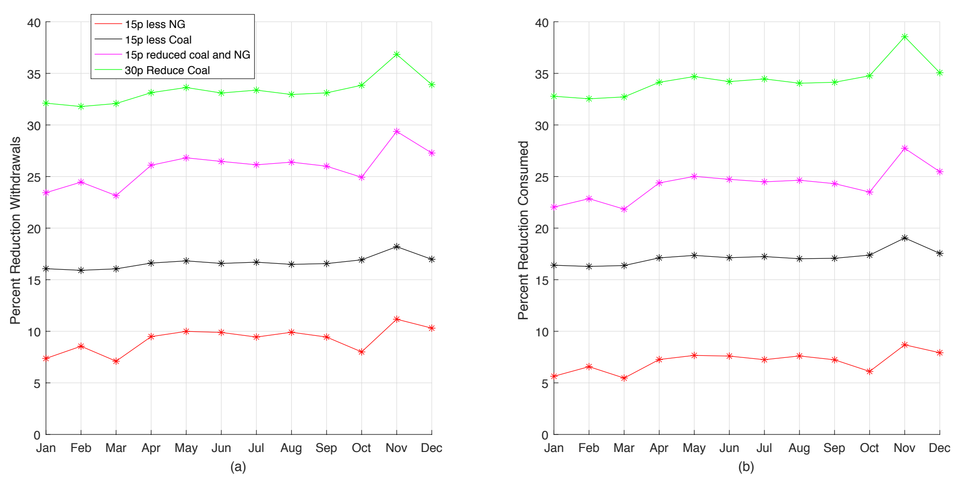

Fig. 4.4. Monthly percent reduction in withdrawals (a) and consumption (b) based on scenarios.

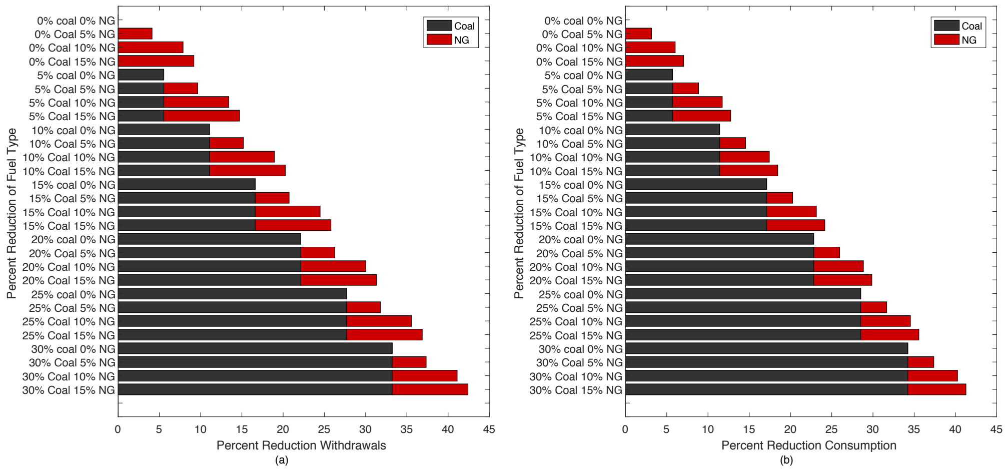

Fig. 4.5. Annual percent reduction in water withdrawals (a) and consumption (b) resulting from reducing thermoelectric power from some percentage of coal and natural gas plants.

in 2015 illustrated in Figure 4.2. It can be seen in Figure 4.4 that the maximum water reduction for 30% power reduction from coal and 15% natural gas is about 44% for withdrawals and 43% for consumption. Looking singularly at the max coal or natural gas reductions, it is found that for withdrawals, 15% total power reduction from natural gas results in about a 9% decrease and a 30% reduction from coal results in around a 34% decrease. Similarly, with consumption, 15% total power reduction from natural gas results in a 7% decrease and 30% reduction from coal results in a 35% decrease. In both cases, the ratio of water use reduction to power reduction is less than one for natural gas and greater than one for coal plants. This further illustrates that reducing coal plants have a much higher overall benefit on reducing water use than natural gas plants. Also, reducing natural gas plants tend to have a higher impact on withdrawals than consumption while the opposite is true for coal plants, although the impact is not as drastic as with natural gas.

The reduction in water use also depend on how plants are dispatched. In a similar analysis, plants are taken offline or reduced based on their capacity factor rather than taking plants offline based on the order of largest to smallest capacity. It was determined that plants with low capacity factors are most likely to be taken offline first if the load requirements decreased; such would be the case with increased rooftop solar. While this would be a more likely scenario, plants with low capacity factors tend to be those with smaller capacities and do not have water use data available like the larger plants and therefore, water factors are inexact based on data but are assumed based on the range found in [25]. Modeling based on this dispatched method yields a variation of 13.6% to 29.6% for coal plants and 3.1% to 14.8% for nature gas powered plants. The number of plants that shut down or reduce capacity based on each scenario is also varied by dispatch method. For the scenario with 30% total power reduction from coal and 15% from natural gas, the number of plants affected over the course of the year varies from 5 coal plants dispatching based on capacity factor versus 1-3 coal plants dispatching based on size. For natural gas reduction, the number of plants affected varies from 24-33 for capacity factor dispatching versus 3-33 for size dispatching. This shows that how plants are dispatched can effect water use in power plants. Further work could be done to optimize how plants could potentially be economically dispatched in order to minimize water use.

For each scenario mentioned above, the total land use area is calculated and presented in Table 4.1. By extrapolating from the study in [31], it was determined that the rooftop area that can be implemented for solar in all the major counties in Utah is found to be 18.5 km^2. From Table 4.1, it can be seen that through implementing rooftop solar generation, the power produced can cover up to 15% of Utah's total power requirements as well as greatly reduce power requirements with solar covering 35 of the 45 percent theoretically reduced. This is a rough estimate of what could potentially be covered by rooftop solar

Table 4.1. Land area needed to produce a given percentage of electrical energy generation with solar PV and the percentage of that required area that could be implemented on rooftops. Beyond 20% of net energy generation, the required area means that additional solar PV penetration is not feasible given current technology in the current Utah electrical grid [33].

Percent Overall Generation Reduced	PV Required Land Area (km^2)	PV Required Land Area (acres)	Percent Area Covered by Potential Rooftop PV
5	5.8	1433	100
10	11.6	2866	100
15	17.4	4300	100
20	23.2	5733	80
25	29.0	7166	64
30	34.8	8599	53
35	40.6	10032	46
40	46.4	11466	40
45	52.2	12899	35

alone. Other methods of renewable generation would have to be implemented in order to account for the rest of the power needed for the other scenarios. Realistically, the maximum amount of power that can be reduced from rooftop solar PV is 20% of peak demand in 2007 for Rocky Mountain Power [33]. Based on Table 4.1 using the rooftop area of all major counties in Utah for solar production, the power reduction will only be about 16% of the total power generated. Therefore, implementing rooftop solar production to its fullest potential in Utah should positively impact the grid for Rocky Mountain Power.

4.6 Conclusion

This analysis illustrates the potential that Utah has for a more solar electrical grid and the effects increased renewable energy would have on water supply. Despite its potential for increased solar power, analyzing the environmental impacts in Utah has its limitations which prevents a more accurate analysis. The power data for PacifiCorp are only obtained on a monthly scale, making it difficult to look for trends in power usage except in a seasonal time scale. More accurate dispatch modeling could be done with more refined data such as hourly or sub-hourly data such as is found in other Balancing Authorities in the WECC region such as CAISO or BPA. Similarly, for environmental data, only the largest plants reported water use data even though other plants had water cooling technologies. This made calculating an overall water use factors for the smaller plants impossible and, instead, had to be approximated based on the range found in [25]. Although the data accounted for about 85% of the total water use data by power generation, a more accurate dispatch model could have been obtained if more water use data were available. Water used for cooling can also vary depending on climate and availability and the data for one year may not be reliably used for another. Warming climates will potentially increase water demands for power plants. Despite the limitations of this analysis, the authors wish to provide a general analysis of how increasing solar power in Utah could affect water supply and could potentially alleviate water stress due to drought or water shortages.

Implementing rooftop solar PV is a popular method of implementing solar energy in the state, but Utah has open spaces where solar panel arrays could be installed to provide more power. Shared solar power generation, off-site solar panels that can be shared by multiple customers, is an alternative possibility for those places where rooftop solar is impractical due to rooftop shape, size, or shading [9]. Implementing large solar parks in place of classic thermoelectric power generating stations would also help to reduce power requirements from current power plants. These methods, as well as implementing other forms of renewable energy, will help to reduce the need for fossil fuels using plants and help to alleviate water use.

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CHAPTER 5

CONCLUSION

Water savings from thermoelectric power generation can be quite substantial and should be considered when looking for ways to conserve water in times of drought or water shortage. These savings can be achieved through more renewable forms of energy which can not only go far in curving emission but also have a large impact on water withdrawals and consumption. Increased solar power, as well as other types of renewable energy, make it possible to save millions of gallons of water per month due to reduced cooling needs of power plants. Using the method introduced in Chapter 3, public awareness of the water used from personal power usage can be increased and possibly encourage more energy efficiency. Using less power overall would be easier and cheaper than changing power infrastructure. The energy reporting methods used in California would be beneficial for Utah to adopt so that energy trends could be more accurately observed as well as help to analyze new ways of increasing energy efficiency. It would also help in modeling the effect that changes in power generating methods would have on the electrical grid, reducing the uncertainty discussed in Chapter 4. By looking at different balancing authorities illustrated in Chapter 3, it can be seen that the more renewable energy connected to the grid, the less water is needed for power.

The feasibility of implementing more solar energy into Utah's power grid has been discussed in Chapter 4. Rooftop solar can potentially cover up to 16% of all Utah's yearly power requirements, reducing water use by up to 18% depending on the fuel type displaced and time of year. Despite the limitations of modeling the energy-water nexus in Utah, this analysis gives an overview of the potential that increased solar power can have on the power sector and Utah's water supply. Potential for solar power does not only come from rooftop area alone, but also from the fact that Utah has many open and flat areas of desert where solar farms can be implemented. Increased solar power can provide Utah with clean power with little maintenance as well as providing the state with improved environmental impacts reducing emissions from plants and houses which can potentially reduce pollution in times of inversion. Advancing renewable energy technology, such as improving energy storage methods, will go far in improving the quality of the power produced by the sun and making a solar future for Utah a real possibility.